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Late Amazonian Wind Regimes and Landscape Evolution in Northern Meridiani Planum, Mars

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Abstract

Aeolian process have dominated the lower latitudes of Mars for billions of years. Aeolian landforms can act as records of current and past climates and landscape evolution processes. The etched deposits of Meridiani Planum, a vast suite of layered bedrock extending from southwest Arabia Terra to Schiaparelli crater, have long been noted to have been eroded by aeolian processes. However, little detailed work on the aeolian landforms of Meridiani Planum beyond the *Opportunity* rover landing site has been done. In this study, I examine wind streaks, aeolian bedforms (including dunes and large ripples), and yardangs in a valley about 370 km northeast of the *Opportunity* site using CTX, HiRISE, and THEMIS imagery in order to extrapolate past and present wind regimes, and to uncover the processes that have driven landscape evolution in layered bedrock on Mars during the Late Amazonian. I measure the orientations of wind streaks, dune slipfaces, ripples, and yardangs to determine their formative wind directions, and make qualitative observations to determine the processes driving landscape evolution. I find wind streaks and dunes suggestive of northeasterly winds, while ripples and valley-interior yardangs indicate east-southeasterly winds. Sawtooth scarp features, considered here to be yardangs, suggest northerly to easterly winds, though the orientations of these features may be more strongly controlled by scarp orientation than wind direction. Since the large, sawtooth-scarp features likely require the longest timescales to form out of all the landforms examined here, they likely represent the oldest wind regime. Dunes and wind streaks are still active across the planet, and may represent modern winds. Ripples and valley-interior yardangs are likely of intermediate age. The wind regime, therefore, may have transitioned from northeasterly, to easterly, and back to northeasterly winds. If climate change on Mars is driven by orbital/rotational changes similar to Earth's Milankovitch cycles, then the landforms in this region may record a full cycle. Examination of HiRISE imagery reveals cliff retreat driven by undercutting enabled by a highly-erodable, high-albedo unit that is also conducive to yardang formation. Sand accumulations are most significant alongside cliffs, and so sand in the region is likely supplied from material weathered off cliffs, sand which can then further abrade and undercut the cliffs. Superposition of material weathered from cliffs on top of ripples implies that cliff retreat continued in this region at least until the period of ripple formation.

1. Introduction

Meridiani Planum, located near the equator of Mars along the prime meridian (Figure 1) hosts an extensive suite of layered, clastic, wind-eroded bedrock often referred to as the etched terrain (e.g., Arvidson et al., 2003). While the aeolian nature of this landscape has been recognized for decades, the details of the landforms, possible records of recent climatic and erosional processes, have not yet been thoroughly studied. At these low latitudes, wind has been the dominant erosive process for billions of years (Day and Kocurek, 2015). A number of different landforms are found within the etched terrain, including plains of fractured bedrock, yardangs, scarps, mesas and buttes, aeolian ripples, and sand sheets. These diverse landforms are evidence of a terrain formed by a variety of processes and preserve a record of the processes that form them. Therefore, the goal of this research is to map the orientations of aeolian landforms within the etched terrain and to make qualitative observations of the terrain in order to interpret the landscape evolution of Meridiani Planum. This is important because aeolian landforms provide a record of the wind conditions at the time that they formed and may therefore be used to test models of atmospheric circulation or record histories of climate change (Sefton-Nash et al., 2014).

The focus of this study is a ~130 km-long, ~5-30-km wide valley in northern Meridiani Planum, in which the lowest part of the etched unit and its contact with the underlying cratered terrain is exposed (Figure 2). The valley floor is sparsely cratered, and boulders weathered from cliffs overlie aeolian bedforms along the boundaries of the valley. These characteristics indicate a geologically young landscape. The valley contains landforms that form on a wide variety of timescales, including wind streaks, ripples, and yardangs, that may preserve a detailed record of Late Amazonian wind patterns and landscape evolution.

2. Background

2.1 Geology of Meridiani Planum

The oldest unit in Meridiani Planum is the dissected cratered terrain (DCT), which formed in the early to middle Noachian period (Figure 3). This unit is described as ‘dissected’ because it is cut by several valley networks thought to have formed from fluvial activity. The DCT forms the base of the regional stratigraphy (Arvidson et al., 2003).

Unconformably overlying the DCT, and dated to the middle to late Noachian, is the etched terrain. It is described as etched because many of its exposures are heavily eroded, often including mesas, buttes, scarps, ridges, and occasionally yardangs. This suggests that the unit is poorly indurated, consistent with a clastic nature. The detection of hydrated sulfate minerals within this unit suggest that it was formed or was altered in the presence of liquid water. In addition, the spatial and temporal association with valley networks in the cratered terrain is consistent with a sedimentary origin, because Martian valley networks were active during the late Noachian when the etched unit was being deposited. The Burns Formation studied by the *Opportunity* is thought to represent the top ten meters of the etched unit (Griffes et al., 2007), and has been interpreted as sandstone formed in dune, sand sheet, and playa environments (Grotzinger et al., 2005). The upper etched unit displays landforms such as buttes, mesas, and yardangs in the southern part of the study area at the edge of a scarp bounding the main valley of the study area.

About 370 km northeast of *Opportunity*’s landing site, and the focus of the study area, is a 130 km-long valley that trends northwest-southeast. Griffes et al. (2007) map the etched terrain as two separate units, as the lower etched plains (LEP) and the upper etched plains (UEP). The LEP is exposed only in this valley, bounded to the south by the plateau of the UEP, and to the north by the cratered terrain. The valley will henceforth be referred to as the “LEP Valley”. Terrain types in the valley include plains of fractured bedrock, yardangs, aeolian sand sheets and dunes, and mesas up to a few hundred meters across.

Overlying the etched terrain to the southwest of the LEP valley are the hematite-bearing plains (Ph). This unit consists of a sediment deposit approximately a meter thick and containing millimeter-scale concretions of hematite. The hematite-bearing plains are interpreted as a lag deposit, the material left behind when part of the etched deposits was eroded during the Hesperian (Griffes et al., 2007). Most of this unit is located outside the study area, and it has no landforms of interest for this study other than ripples that may indicate recent wind direction.

2.2 Aeolian Landforms

Aeolian landforms are abundant on Mars. These include erosional landforms such as yardangs, mesas, and scour, and depositional landforms such as dunes, ripples, and transverse aeolian ridges (TARs). Wind streaks, both bright and dark, in the lee of obstacles are also common on Mars. The main landforms of interest in this study are wind streaks, yardangs, and aeolian bedforms (including dunes and ripples).

Wind streaks (Figure 4) are linear regions of distinct albedo (lighter or darker than their surroundings) that extend downwind of topographic obstacles such as craters or buttes. They are formed by the settling and subsequent removal of dust in the aftermath of global dust storms. Bright streaks are formed where an obstacle shields the area downwind from winds strong enough to remove dust from the surface, while dark streaks form where the influence of the obstacle causes dust to be removed by the wind. Many wind streaks on Mars have been observed to actively change after dust storms (Thomas and Veverka, 1979; Edgett, 2002). Dark streaks are absent from the study area, but bright streaks are found on the cratered unit to the north of the LEP valley.

Yardangs (Figure 5) are streamlined features formed when consolidated material such as bedrock is abraded by sand grains moved by the wind. They form in regions with strong unidirectional winds. In yardang fields, winds are focused into the inter-yardang valleys, where the floors of the valleys are down-cut by abrasion, increasing the relief of the yardangs. Lag deposits or sediment eroded off the sides of the yardangs may accumulate in these valleys, armoring the surface from further erosion. Deflation, the removal of silt or clay-sized clasts from the rock by the wind, can erode the tops of the yardangs and reduce their relief. Abrasion at the front and sides of the yardangs, as well as collapse of the slopes caused by removal of material, make the yardangs shorter in length and narrower over time (Barchyn and Hugenholtz, 2015). Yardangs come in a wide variety of morphologies, and characteristics such as the spacing between them serve as indicators of the yardangs' maturity (Wang et al., 2018). These features are present in scarps along the edges of the LEP valley, and in bedrock exposures throughout the valley floor.

Aeolian bedforms (Figure 6) are depositional features. The term refers to a wide variety of landforms, including dunes, ripples, and transverse aeolian ridges (TARS). The large dark dunes often found in topographic lows on Mars are seldom found in this study area, with only a few along the northern boundary (Figure 6B). All other bedforms – being long, narrow, and sharp-crested - will be referred to as "ripples" (Figure 6A). Patches of sand with aeolian bedforms are present throughout the LEP valley, particularly at the margins of the valley and in depressions up to tens of meters across.

2.3 Recent Climate Change on Mars

Simulations show that Mars experiences fluctuations in its orbital elements and obliquity (axial tilt) similar to the Milankovitch cycles that cause glacial and interglacial periods on Earth. These changes are predicted to occur on timescales of Ma to tens of Ma. The climatic effect of such changes would be changes in the distribution of ice across the planet. Physical evidence that these changes actually occur come in the form of alternating light and dark layers in the polar caps. Light layers are ice, deposited during periods where ice was more stable at the poles, while dark layers are dust, deposited when ice sublimated from the poles. Other evidence includes glacial deposits with ages correlating with a period of high obliquity, in areas where ice would be expected to be deposited in periods of high obliquity (Montmessin, 2006). These shifts in climate could have also caused changes in the dust cycle and wind directions.

Fenton et al., 2015, based on observations of bedforms and wind streaks in the vicinity of the Mars Exploration Rover *Opportunity* landing site, found evidence that the wind regime in Meridiani Planum has shifted over the past several hundred ka. Since the *Opportunity* site is about 370 km southwest of the study area, similar changes may have left their mark on the landscape.

3. Methods

3.1 Images and Mapping

I used data from two different instruments on the Mars Reconnaissance Orbiter (MRO) spacecraft: (1) the Context Camera (CTX) and (2) the High Resolution Imaging Science Experiment (HiRISE), as well as nighttime infrared imagery from the Thermal Emission Imaging System (THEMIS) on the 2001 Mars Odyssey spacecraft. CTX data cover the entire study area about 6 meters per pixel (Malin et al., 2007). HiRISE data only partially cover the study area, perhaps 10 to 20 percent, roughly estimating, but has a resolution of up to 25 centimeters per pixel (McEwen et al., 2007). THEMIS imagery also covers the entire study area at a resolution of 100 meters per pixel (Christensen et al., 2004).

Images were loaded and investigated using the Java Mission Analysis and Remote Sensing (JMARS) software developed by Arizona State University (Christensen et al., 2009). With a resolution sufficient for the identification of relevant landforms, CTX imagery was the primary dataset used for mapping. The higher resolution of HiRISE enabled the examination of meter-scale morphological characteristics. These may include surface texture (e.g. regolith vs. fractured bedrock), orientations of small aeolian bedforms, or loose blocks on or near mesas or yardangs that may indicate the presence of cap rock (Zimbelman and Griffin, 2010). Fine-scale properties observed in HiRISE were extrapolated to features visible at CTX resolution, allowing for a more complete characterization of the study area. THEMIS imagery was used to distinguish surface materials on the basis of thermal inertia, particularly for distinguishing areas of sand cover.

Features were mapped in JMARS using custom shape layers. Aeolian bedforms were approximated as straight lines connecting one end of the ripple crest to the other. Yardangs were also mapped as straight lines, aligned with the long axis in the case of linear, ridge-shaped yardangs, and aligned with the V-shape of the more blunt yardangs. Scarps were mapped as lines consisting of multiple segments. Polygons were used to map sand cover and select geomorphic units.

Once mapping in JMARS was complete, the resulting data was exported to ArcGIS Pro, which was used to plot the orientations of the landforms on histograms.

3.2 Identification of Landforms

Four types of aeolian landform were mapped in this study: wind streaks, dunes, ripples, and yardangs.

Wind streaks were identified as elongated regions of high-albedo with topographic features such as craters or buttes at one end.

Dunes were identified as broad, low-albedo features with relatively small ripples visible at HiRISE resolution and having at least one slipface.

Ripples were identified as having linear, curvilinear or sinuous crests aligned parallel to subparallel to nearby, similarly sized features occurring with a consistent spacing between crests. Aeolian bedforms also have smooth surfaces at the resolutions of the data used in the study, consistent with a composition of unconsolidated sediment.

The term yardang is used in this study to describe erosional features aligned to the wind. Features identified as yardangs possess one of three morphologies: linear, V-shaped, and sawtooth scarps. Linear yardangs are elongated bedrock ridges with positive relief, and rarely have any asymmetry that could be used to determine the precise wind direction, and so these yardangs are 180-degree ambiguous recorders of wind direction. V-shaped yardangs are highly asymmetric, with a steeper side shaped like a V (or sometimes a U) when viewed from above, the other side being a gentle slope grading into the surrounding topography. The tip of the V forms the steepest part of the yardang. The steeper side was interpreted to point upwind, and so V-shaped yardangs are unambiguous recorders of wind direction. Sawtooth scarps are similar to V-shaped yardangs in their general shape, but differ in that they are part of a larger cliff or scarp. They are similar in appearance to the features referred to as “capes” that the *Opportunity* rover observed at Victoria Crater (Grant et al., 2008).

4 Results

Wind streaks occur just to the north of the LEP valley, extending downwind of features such as craters and buttes on the cratered terrain. All wind streaks mapped were bright; no dark wind streaks were observed in the study area. Most wind streaks are oriented toward an azimuth between 195° and 218°, with a few outliers (Figure 7).

Only three dunes were observed in the study area, along the northern edge of the LEP valley. One of these dunes has a single slipface, oriented about east-west. The other two have two slipfaces each – one oriented east-northeast-west-southwest, the other oriented north-northeast-south-southwest (Figure 6B).

Ripples occur ubiquitously throughout the study area, but are most concentrated at the edges of the LEP valley, where areas of low thermal inertia determined from THEMIS images may represent thicker accumulations of sand than occur in the valley interior (Figure 8). Ripples in the valley interior tend to be smaller and more isolated, with small ripple fields occurring in craters and depressions. When the orientations of ripple crestlines are plotted on a histogram, they form a bell-curve distribution peaking at an azimuth of about 20° (Figure 9).

Yardangs were divided into two categories: valley-interior yardangs (Figure 5A), and sawtooth scarp yardangs (Figure 5B). Valley-interior yardangs, as their name implies, are found in bedrock exposures on the floor of the LEP valley. They vary in morphology, being either linear, V- or U-shaped, or teardrop-shaped. Valley-interior yardangs occur in multiple types of bedrock, but most prominently occur in a light-toned unit most commonly exposed near the edges of the valley and near mesas. The long-axis orientations of valley-interior yardangs display a bimodal distribution, with a larger peak at an azimuth of about 270°, and a smaller peak at about 210° (Figure 10).

Yardangs of the sawtooth scarp variety occur primarily along the southern boundary of the LEP valley. In HiRISE images, these features appear to consist of a capping unit overlying a lighter-toned unit that forms the base of the scarp, the same light-toned unit that also prominently forms many of the valley-interior yardangs. Blocks of the capping material are often found lying on top of bedrock or rippled sand deposits below the cliffs (Figure 11). Based on shadow lengths, sawtooth scarp yardangs can rise well over 100 m above the adjacent valley floor. The orientations of sawtooth scarp yardangs also fall along a bimodal distribution, with a larger peak at about 190°, and a smaller peak at about 270° (Figure 12). Their orientations are roughly perpendicular to the trends of the scarps they are found on.

5 Discussion

5.1 Wind Regimes

Wind streaks, pointing toward the southwest, indicated winds coming from the northeast. The dunes with two slipfaces suggest a bimodal wind regime,with one wind coming from the north-northwest, and the other coming from the east-southeast. The net combination of these two winds is northeasterly, similar to the streak-forming winds. Therefore, the dunes and wind streaks may have formed in the same wind regime. Considering that these two types of landforms tend to be active across the planet (Thomas and Veverka, 1979; Chojnacki et al., 2014), they may represent modern winds coming from the northeast.

The orientations of ripples suggest that they were formed by wind coming from the east-southeast or west-northwest. While the lack of strong asymmetries in the ripples makes it difficult to determine which of these two directions the wind came from, comparison to ripples mapped in other parts of Meridiani Planum (Fenton et al., 2015) and in Jezero crater (Day and Dorn, 2019) suggest that the winds are east-southeasterly.

Valley-interior yardangs are mostly oriented east-west. Some yardangs display steeper slopes on their east ends, indicating that they were formed by easterly winds. This coincides with the wind regime interpreted from the ripples, and so these two types of landforms likely formed in the same wind regime. Given the longer timescales require to form yardangs compared to dunes and wind streaks, this easterly wind regime likely predates the northeasterly wind regime. A minority of valley-interior yardangs are oriented north-northeast-south-southwest. Since yardangs become more isolated and widely-spaced as they mature (Wang et al., 2018), the fact that yardangs of this orientation are not as numerous may indicate that they formed in an even older northeasterly or southwesterly wind regime.

Sawtooth scarp yardangs are mostly oriented north-south, with a minority oriented east-west. Given the similarity between the bimodal distributions of the orientations of the two classes of yardang, it is tempting to conclude both yardang types were influenced by similar wind regimes. However, sawtooth scarp yardangs are oriented perpendicular to the scarps they occur on; their orientations may be influenced more by scarp orientation than by wind direction. There are no significant morphological differences between sawtooth yardangs of different orientations, and the smaller number of east-west sawtooth yardangs is most likely due to the fact that there are relatively few east- and west-facing scarps in the LEP valley. With these facts in mind, the fact that valley-interior and sawtooth scarp yardang orientations both show bimodal distributions with peaks at similar azimuths may be coincidental. As for the wind regime the sawtooth scarp yardangs formed in, the fact that the orientations of these features are strongly controlled by scarp orientations limits their reliability as indicators of wind direction. However, they are most prominently found on north- and east-facing scarps, and are either poorly developed or absent on south- and west-facing scarps. This may mean that the sawtooth scarp yardangs were formed in a net-northeasterly wind regime.

Measurements of aeolian landforms in the LEP valley clearly indicate that the wind regime has changed in the geologically recent past. I interpret that the oldest winds came from the northeast, forming the sawtooth scarp yardangs and the northeast-southwest valley-interior yardangs. Then, some change in climate caused the winds to come from the east, forming the ripples and the majority of the valley-interior yardangs. Finally, more recent (and possibly modern) winds include east-southeasterly and north-northwesterly components that add up to a net-northeasterly wind regime. If changes in wind direction in the the recent history of Mars were caused by orbital forcing, then the transition from northeasterly, to easterly, and then back to northeasterly winds recorded by landforms in the LEP valley may represent a full cycle, analogous to an interglacial-glacial-interglacial cycle on Earth.

5.2 Landscape Evolution

The bright, yardang-forming bedrock that forms the bases of the cliffs bounding much of the study area is interpreted to be poorly indurated and/or composed of soft, easily-abraded material, based on its tendency to form yardangs and the lack of blocks weathered from this unit. Two layers of this material are identified in the study area, one directly overlying the dark, cratered unit that forms the basement of the regional stratigraphy, and another within the etched deposits, underlying the caprock that forms the plateau to the south of the study area and overlying most of the bedrock on the valley floor. The easily-eroded nature of this material may be the reason behind the cliff retreat that has occurred in this study area. Relief in the valley is largely limited to less than tens of meters, except where the bright, yardang-forming material is found, where cliffs can exceed 100 meters in height. The probable high erodability of the yardang-forming material and its stratigraphic occurrence beneath a mechanically stronger capping unit would be conducive to undercutting, collapse, and cliff retreat. These processes enabled by the bright, yardang-forming unit may have formed the LEP valley, with cliff retreat possibly initiated along the contact between the cratered unit and the etched unit in the northern part of the study area. In addition, the fact that thick accumulations of sand, as indicated by areas of low thermal inertia in THEMIS imagery, are most common along these cliffs suggests that the supply of sand that forms the ripples comes from cliff retreat. In the period of ripple formation, these mobile sand grains would have been able to abrade the bright bedrock, leading to further undercutting and collapse. Much of this sand would have had to have been transported out of the valley, given that much of the valley floor is sand-free. Cliff retreat in the LEP valley, then, may be an important source of sand in the wider region.

The timing of some of the aeolian processes that operated in this region can be constrained by the superposition of weathered blocks of caprock on top of ripples. The fact that such blocks have yet to be buried by large ripples suggests that the most recent cliff retreat postdates the most recent migration of large ripples. Alternatively, both processes may have occurred contemporaneously, with blocks from the most recent rockfalls being largely unaffected by ripple migration, while blocks from older rockfalls have either been buried or weathered and eroded away by the saltating sand. Earlier work by Fenton et al. in 2015 in a part of Meridiani Planum closer to the *Opportunity* landing site determined that easterly winds were forming ripples as recently as 200 ka. If the easterly wind regime in this study and in the study by Fenton et al. are the same, this means that ripple formation and cliff retreat in the LEP valley were also active up to 200 ka.

Conclusion

Aeolian landforms in the LEP valley within Meridiani Planum record changing wind regimes in the Late Amazonian. The oldest of these wind regimes was probably northeasterly, followed by a period of easterly winds that may have lasted up until ~200 ka. These easterly winds formed large ripples in sand deposits, and the mobile sand abraded bedrock to form yardangs and undercut cliffs. Cliff retreat would have supplied sand both within the valley and in the wider region. More recently, the winds once again became northeasterly, with east-southeasterly and north-northwesterly components. These measurements and observations are helpful for understanding how the climate of Mars has changed in the geologically recent past, and how the wind has shaped the landscape of Meridiani Planum.

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Figures

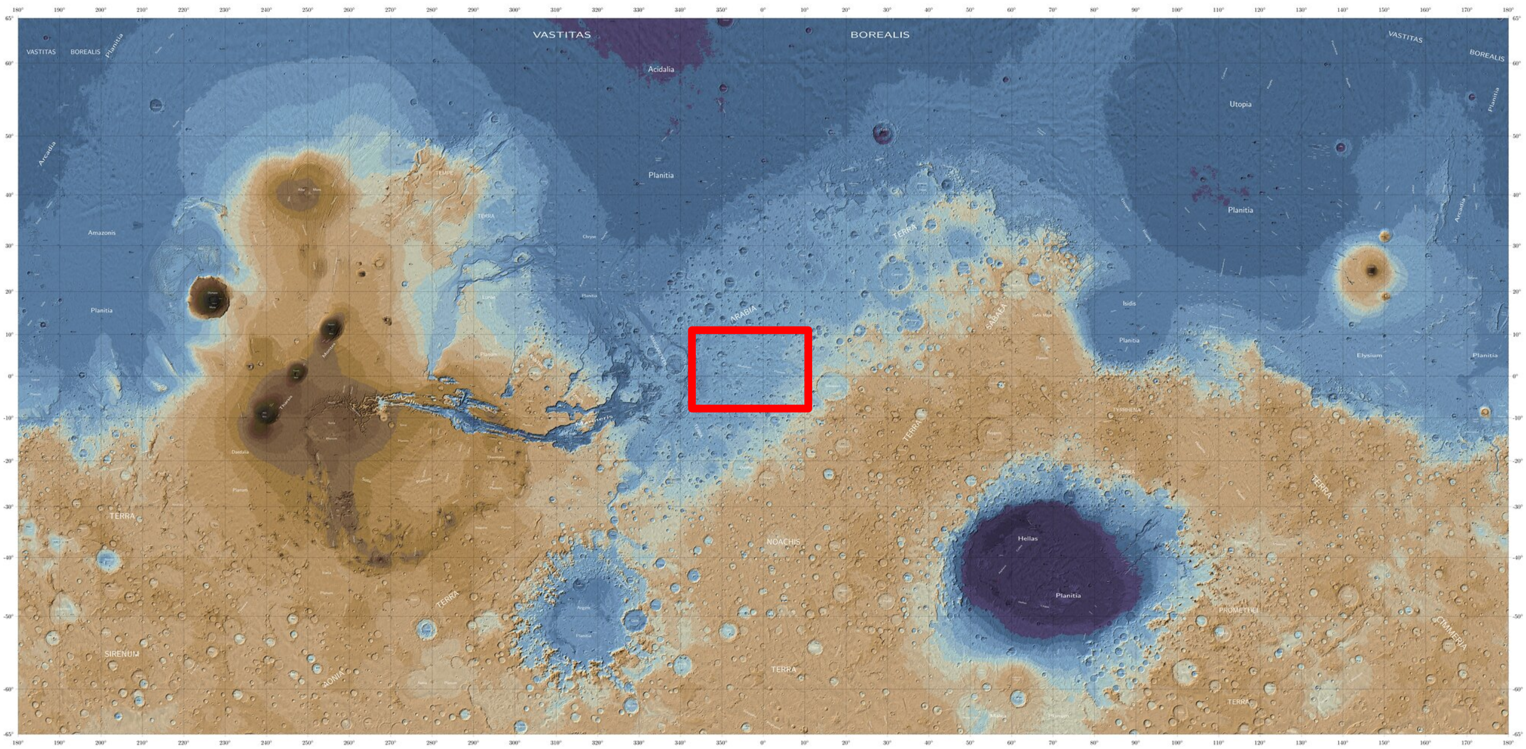

Figure 1. Global topographic map of Mars in Mercator projection, showing the location of Meridiani Planum (red rectangle). The highest elevations have a dark brown color, while the lower elevations have a dark purple color. The highest elevation (Olympus Mons) is 21.2 km, while the lowest (Hellas Planitia) is -8.2 km. Map created by Daniel Machacek.
Credit: NASA / JPL / GSFC / ASU / USGS / ESA / DLR / FU Berlin (G. Neukum) / Daniel Macháček.

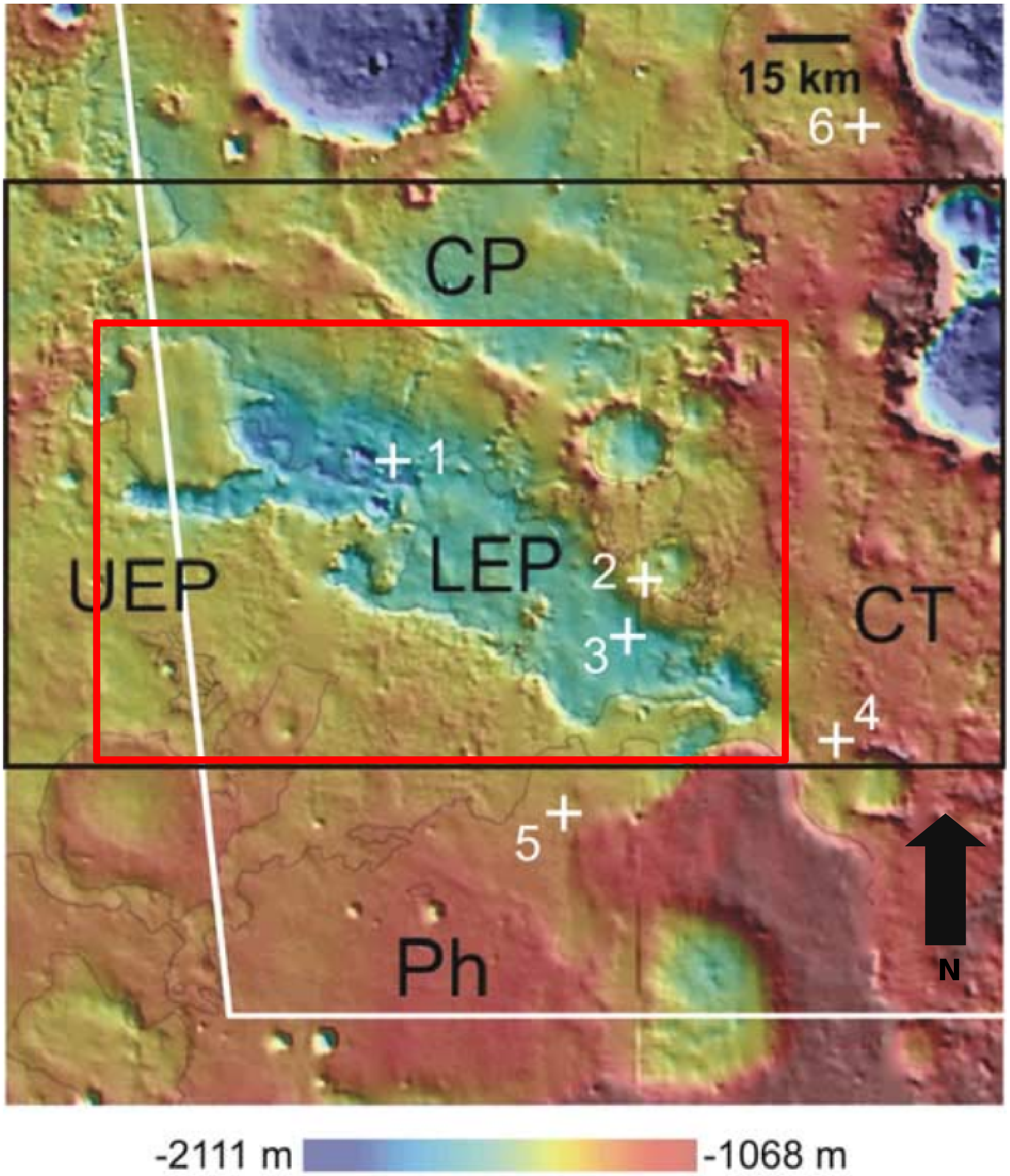

Figure 2. Topographic map of the study area within Meridiani Planum derived from MOLA data. The valley in the center of the map, marked as Lower Etched Plains (LEP), is where the lower unit of the etched deposits is exposed. The valley is approximately 130 km in length, with the longest axis oriented northwest-southeast. The red rectangle shows the approximate bounds of the study area. (Figure from Griffes et al. (2007).

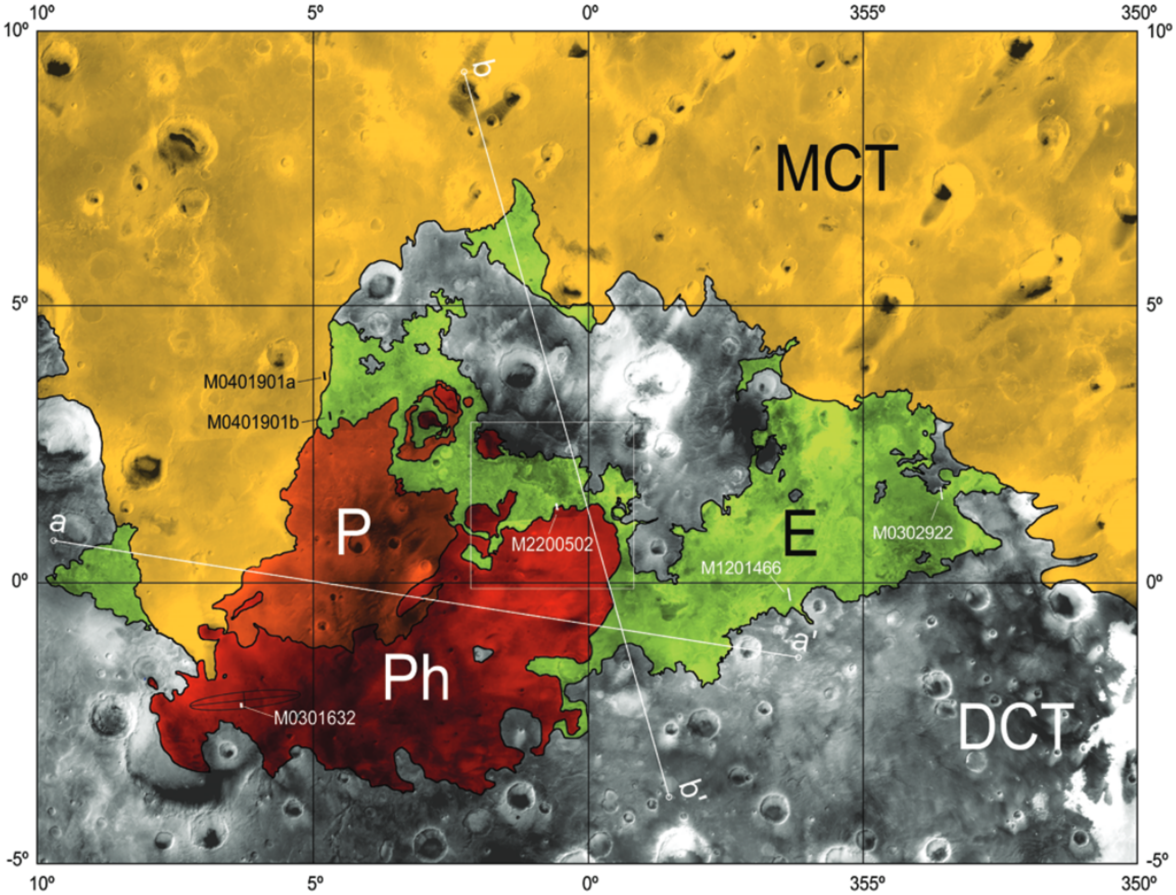

Figure 3. Geologic map of Meridiani Planum. The dissected cratered terrain (DCT; grey unit) forms the base of the regional stratigraphy, and is unconformably overlain by the etched terrain (E; green unit). Thin deposits of loose sediment (P and Ph) overly the etched terrain, and an aeolian dust mantle (mantled cratered terrain; MCT) overlies the cratered terrain in the north. (Figure from Arvidson et al. (2003).

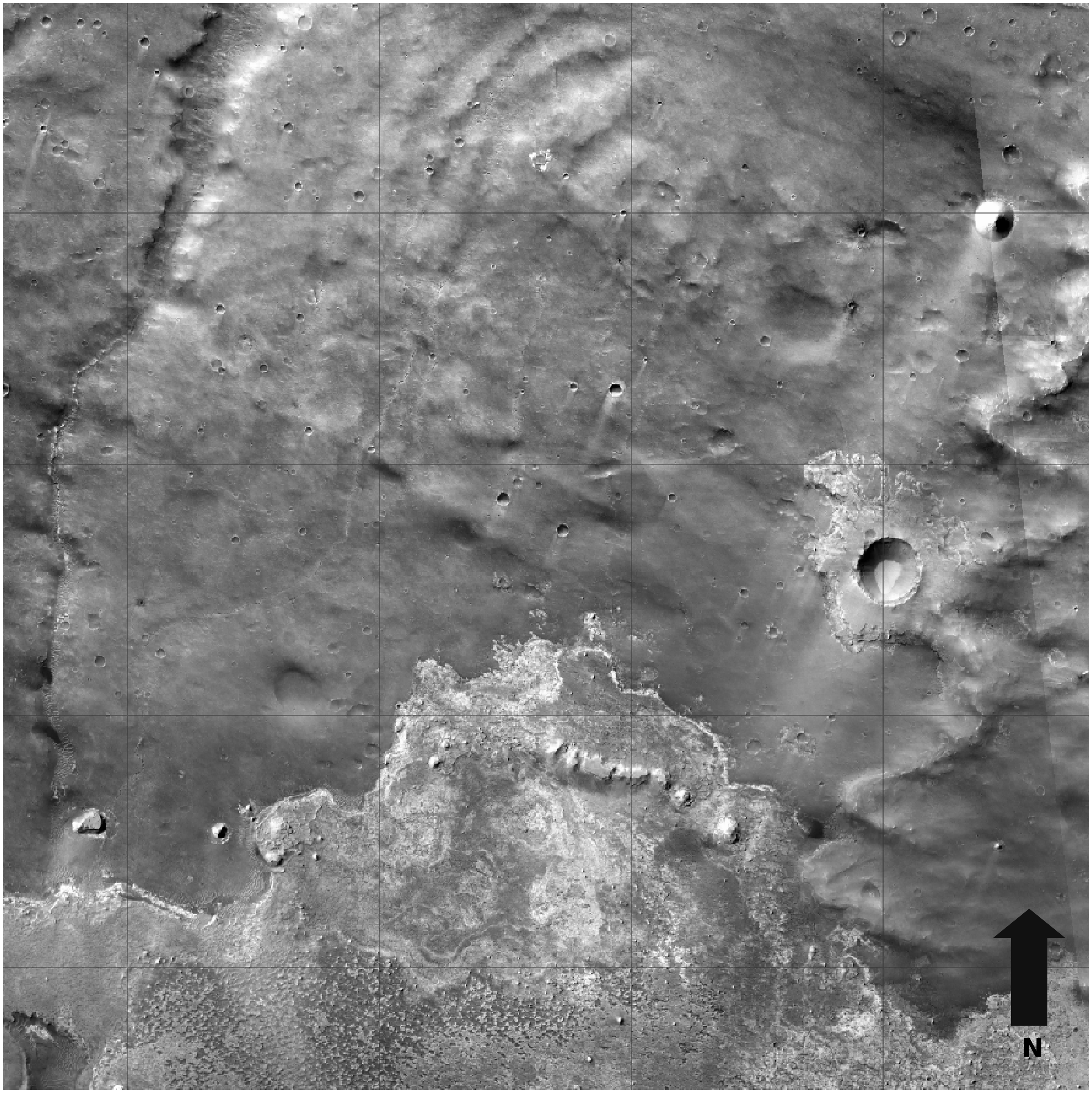

Figure 4. CTX image of bright wind streaks just to the north of the LEP valley, extending to the southwest from craters and buttes. Grid squares are 6 x 6 km. Screenshot from JMARS.

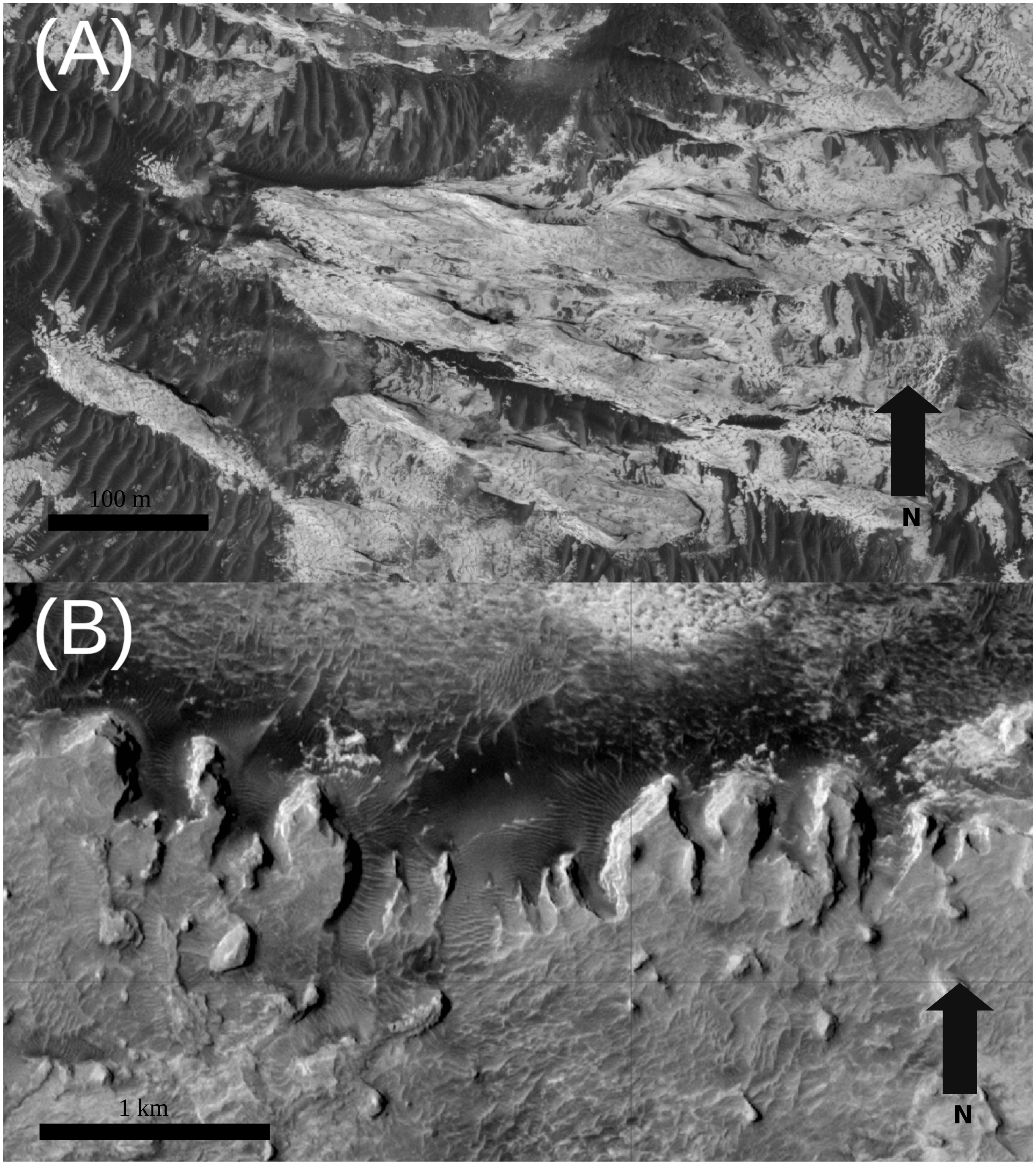

Figure 5. The two types of yardang investigated in this study. (A) HiRISE image of valley-interior yardangs. (B) CTX image of sawtooth scarp yardangs. Screenshots from JMARS.

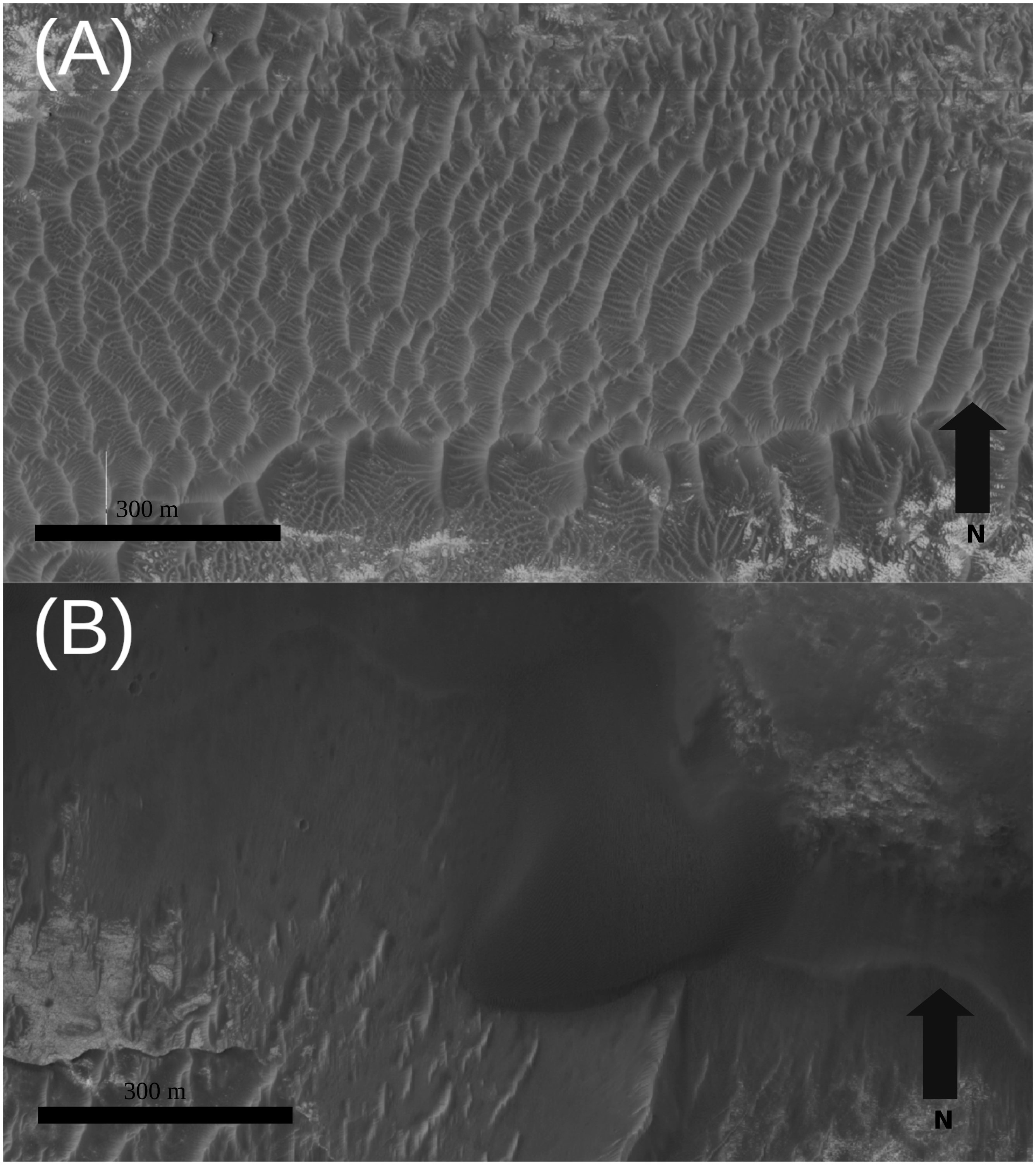

Figure 6. The two types of bedform investigated in this study. (A) HiRISE image of ripples. (B) HiRISE image of a large, dark dune with two slipfaces, with ripples to the southwest. Screenshots from JMARS.

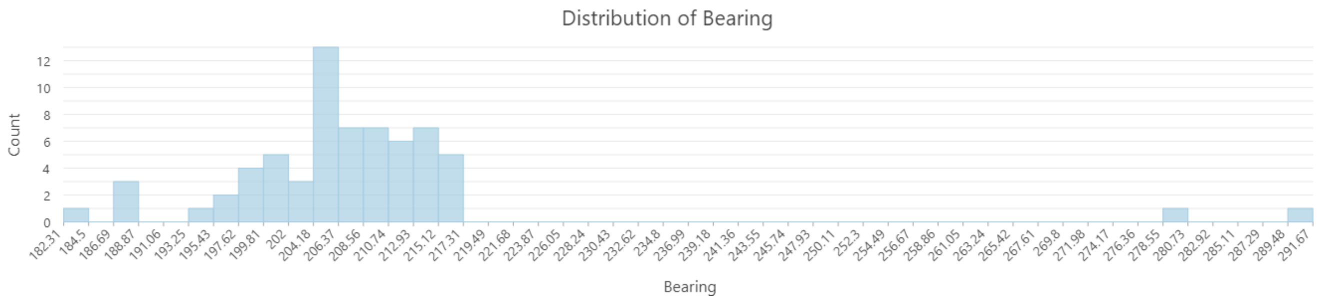

Figure 7. Histogram of wind streak bearings. Chart created in ArcGIS Pro.

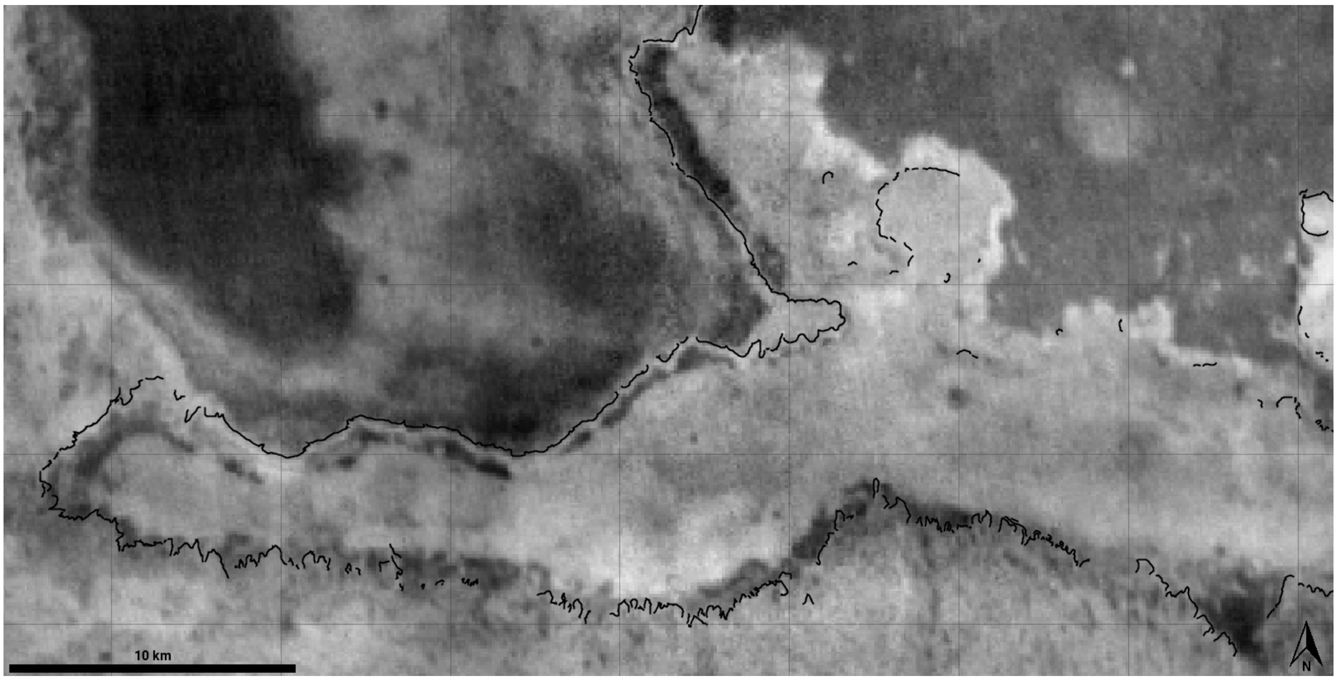

Figure 8. THEMIS nighttime infrared image of the western end of the LEP valley. Black lines mark scarps at the edge of the valley, with higher elevations to the south, west, and northwest. Dark areas in the THEMIS imagery adjacent to the valley-bounding scarps represent surfaces with low thermal inertia and are interpreted as areas of thick sand accumulation. Screenshot from JMARS.

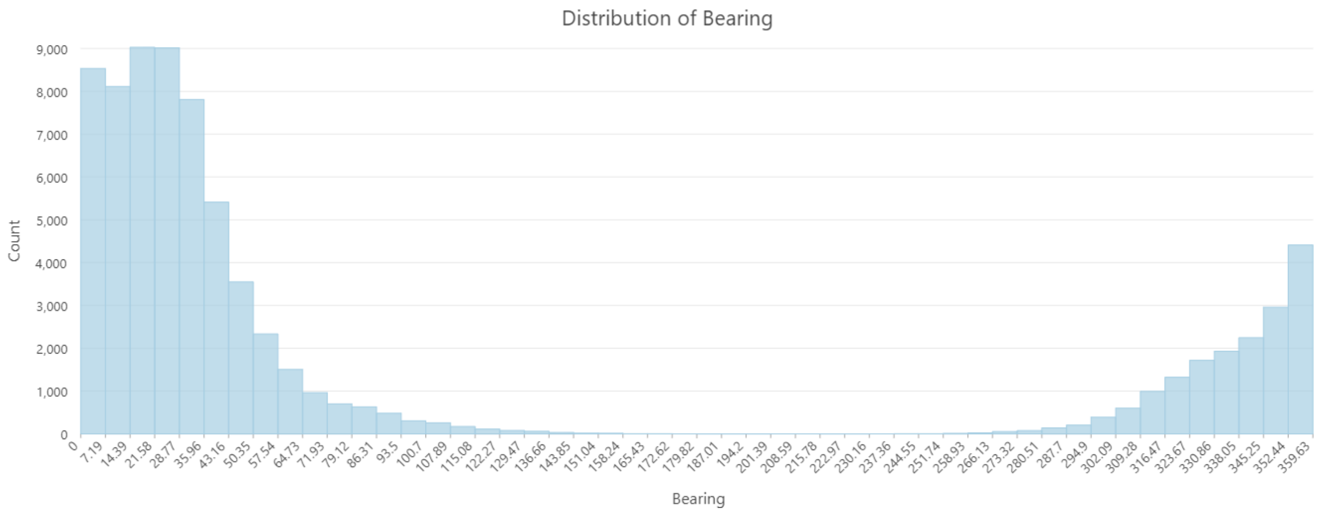

Figure 9. Histogram of ripple crestline bearings. Chart created in ArcGIS Pro.

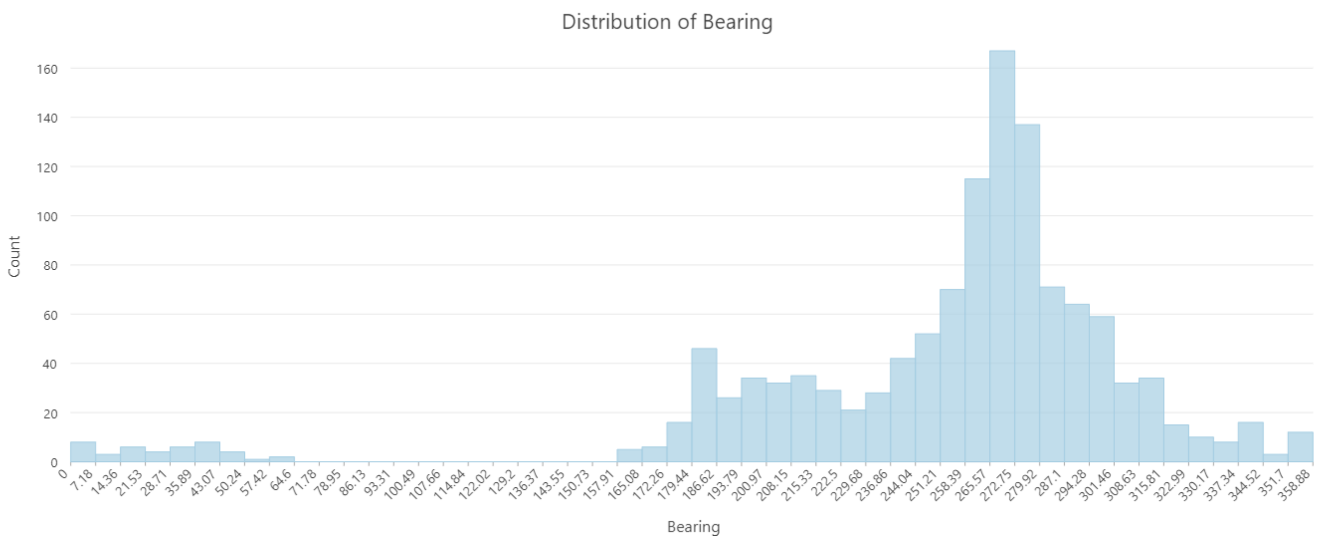

Figure 10. Histogram of valley-interior yardang long-axis bearings. Chart created in ArcGIS Pro.

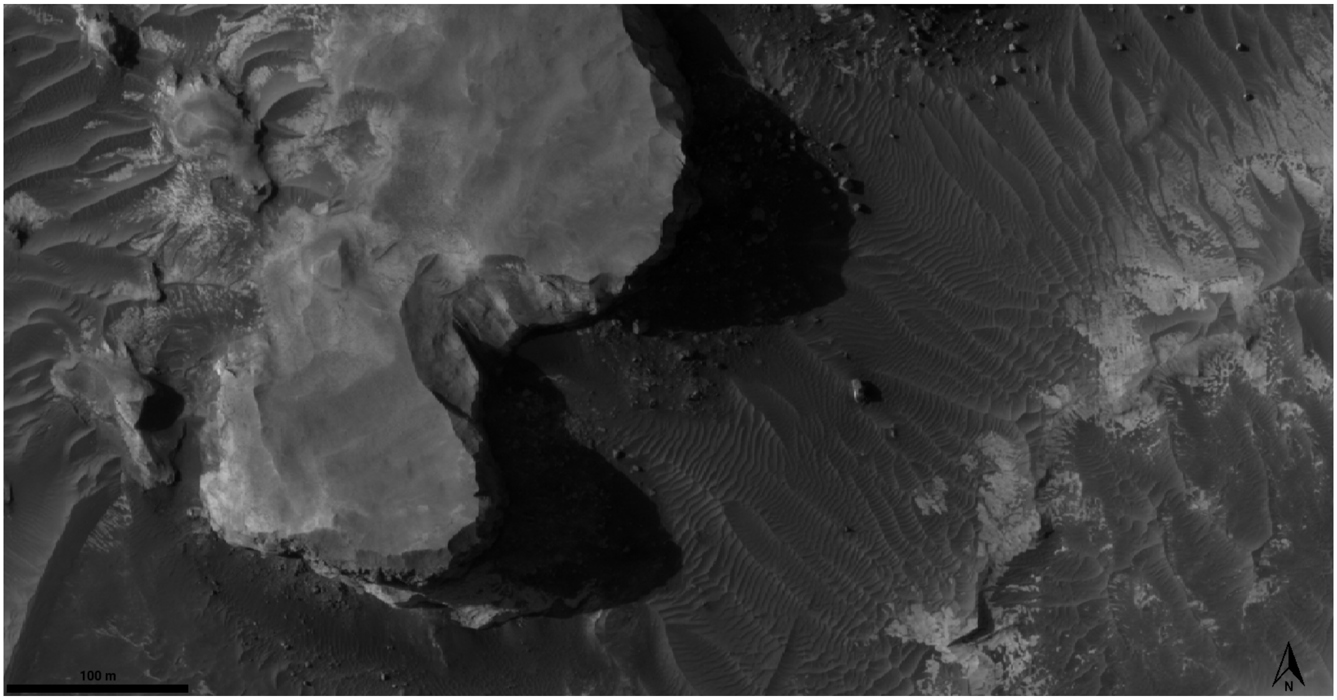

Figure 11. HiRISE image of boulders and other debris weathered off of cliffs at the edge of the LEP valley overlying ripples. The light-toned unit that is often yardang-forming in other parts of the valley is exposed on the east side of this image, and in the southernmost cliff, where it is overlain by darker caprock. Screenshot from JMARS.

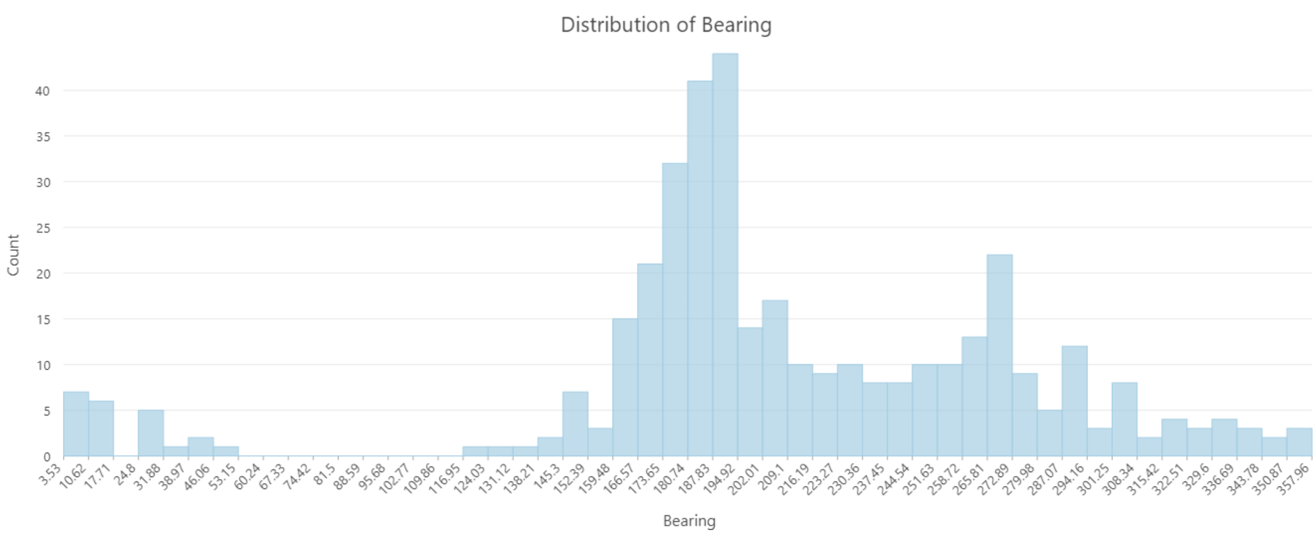

Figure 12. Histogram of sawtooth scarp yardang orientations. Chart created in ArcGIS Pro.